DOI 10.1007/s10891-016-1399-3

Journal of Engineering Physics and Thermophysics, Vol. 89, No. 2, March, 2016

TRANSIENT PHENOMENA IN PROBE MEASUREMENTS IN LOW-DENSITY HELIUM AND OXYGEN PLASMA

S. A. Gutsev

UDC 533.9.082.5

Measurements of the probe characteristics in the pulsed mode in oxygen and helium plasma are presented. The question on the thickness of the near-probe space charge layer in the electron–ion, electron–ion–ion, and ion plasma is discussed. It has been shown that the presence of negative ions in the plasma leads to a drastic decrease in the thickness of the ion layer. A model of the formation of a near-probe layer in nonstationary low-pressure plasma is proposed. It been shown that a space charge layer is formed in the time of 5–6 collisions of ions with neutral particles. It has been illustrated that the displacement current has a linear dependence on the potential applied to the probe. The question concerning the value of the dielectric constant of the plasma is discussed.

Keywords: *low-pressure discharge, ion–ion plasma, Langmuir probes, volt–ampere characteristic, space charge layer.*

Introduction. With the use of probe methods of plasma diagnostics, one obtains local values of the most important parameters — the plasma potential, the concentration of charged particles, their temperature, as well as the particle energy distribution function. In this area of diagnostics, the most developed theories are the collisionless and diffusion theories of charged particle motion onto the probe [1]. Unfortunately, the problem of probe diagnostics under intermediate conditions where the free path of ions is comparable to the thickness of the space charge layer $\lambda \approx h$ has not been solved completely. Meanwhile, this regime of particle motion is often realized under experimental conditions, and processing of curves according to these theories leads to serious errors obviously fall outside experimental errors [2] that are especially manifest in investigating a plasma containing negative ions [3–5]. For correct determination of the plasma parameters according to the probe theories it is necessary to determine the ratio of the space charge layer thickness to the particle free path, since this value determines the applicable theory, which leads to the elimination of methodological errors [6]. The layer thickness can most easily be estimated by the method of time measurement of the probe current pulse. To this end, a voltage pulse is applied to the probe, and the current response is recorded with a high time resolution. It should be emphasized that the transient phenomena accompanying the formation of the near-probe layer are the least studied area of probe diagnostics. A qualitative description of these processes in a plasma consisting of electrons and positive ions is given in [1] with references to [7–10]. The authors investigated the volt–ampere characteristics (VAC) of the charge in the steady-state regime, and then at various points of the characteristic a signal in the form of a step was applied to the probe. The thus arising current pulse was recorded on the oscilloscope screen. This surge is due to the redistribution of ions and electrons in the near-probe layer, i.e., the charges separate, and their polarization occurs. The time needed for the space charge layer to be formed is approximately equal to the ratio of the layer thickness to the thermal velocity of ions:

$$t \approx h/v_t \ . \tag{1}$$

It depends on the ion mobility and on the gas pressure. For instance, in He at $P = 1.2$ torr its value is about 1 μs. In the high-pressure charge, surges exceeding the saturation current are not observed. In such a plasma the current of charged particles is limited by collisions in the plasma and cannot increase stepwise. As the authors of [1, 7–10] note, surges are created by the displacement current that is due to the capacitive impedance formed by the probe and its surrounding layer. Probe measurements in a plasma with negative ions represent a new material that permits a deeper analysis of the formation mechanism of space charge layers.

The aim of the present work is to clarify the role of charged particles in the formation of a near-probe layer, estimate its thickness, as well as determine the main elementary process due to which a redistribution of charged particles in the layer occurs. The above factors undoubtedly lead to an improvement of the probe methods.

V. A. Fok Research Institute, St. Petersburg University; email: gsa_ges@mail.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 89, No. 2, pp. 464–469, March–April, 2016. Original article submitted September 13, 2014.

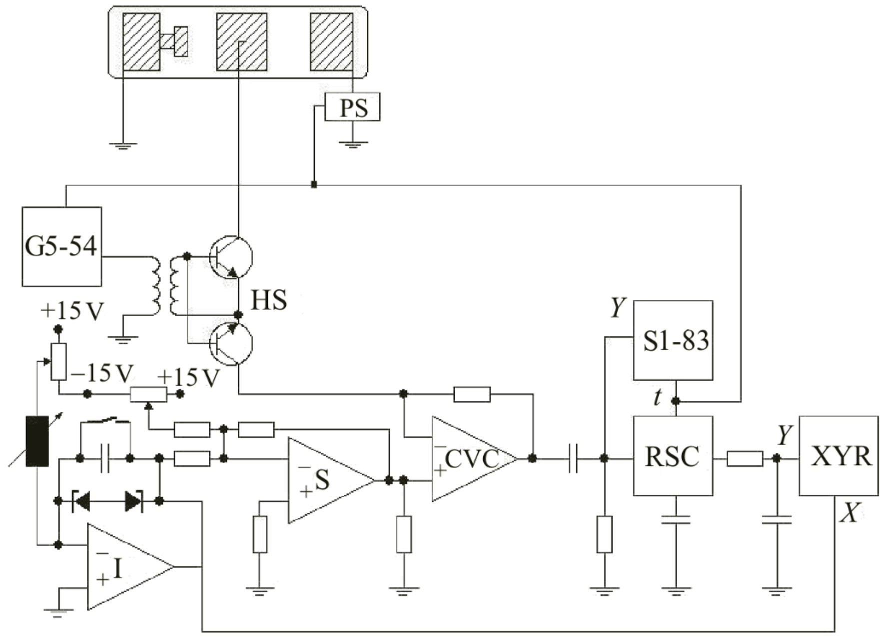


Fig. 1. Basic probe current measuring circuit.

Experimental Facility and Plasma Conditions. Let us consider a low-pressure plasma in helium and oxygen. The charge was set up in a glass tube of radius R = 1.6 cm and length 40 cm.

Measurements in helium were made at a steady discharge current of 2 mA; the gas pressure was 0.3 torr. For the cathode, we used a mobile steel cylinder fixed at a distance of 14 cm from the anode. For the diagnostic electrode located in a hollow near-wall anode of length 2.5 cm, a steel cylinder was used: the probe radius was 0.5 cm and its length was 2 cm. The diagnostics was complemented by VAC measurements by a cylindrical molybdenum probe of radius 0.01 cm and length 0.7 cm. The processing of the characteristics permitted determining the particle number density, which was measured to be $2 \cdot 10^8$ cm^{-3}, as well as the temperature of electrons 0.6 eV.

Measurements in oxygen [11] were made in the afterglow at a discharge current of 80 mA, a pulse length of 50 μs, and a gas pressure of 0.07 torr. For the cathode and anode, we used hollow nickel electrodes of length 4 cm and radii 2 and 1 cm, respectively. Diagnostics was carried out by a cylindrical probe from molybdenum: the probe radius was 0.01 cm and its length was 1.5 cm. For probe measurements, we constructed an electronic device whose basic diagram is given in Fig. 1.

The diagnostic device consisted of a high-voltage switch (HS), a current-to-voltage converter (CVC — KR544UD2A), and a summator (S). The voltage needed for VAC measurements was formed on an integrator (I). The G5-54 generator pulse opened, by means of the isolation transformer, the switch (HS), through which the voltage from the summer was applied to the probe. At the CVC output, the converted current was recorded by an S1-83 oscilloscope and arrived at the retrieval-storage circuit (RSC) and further at an *x–y*-recorder for graphic recording of the probe VAC. The time resolution of the measuring circuit was determined by the S1-83 oscilloscope (for the oxygen plasma) and was measured to be 0.2 μs; the current resolution was 0.01 mA. In the case of the helium plasma, to decrease errors, the probe diagram was maximally simplified; it consisted of only one high-speed CVC. To initiate this discharge, we used a high-pulse voltage source (PS), which enabled us to bring the ground closer to the floating potential of the probe. The pulse signal was formed by an SFG2110 generator, and the $I(t)$ response was recorded by a Textonic 1012B digital oscilloscope. The above devices had a good operation speed (transmission band of 100 MHz) and permitted obtaining the investigated signal immediately in digital format. This possibility was used to take into account the instrument function of the measuring circuit.

Experimental Data. Figure 2 shows the dependences $I(t)$ in helium (a) and oxygen (b).The time of the current surge due to the formation of a near-probe layer in the helium plasma was 0.6–0.7 μs, and in the oxygen plasma it was 1.3–5 μs. Oscilloscopic measurements of the probe current were taken at two points of the oxygen plasma afterglow, 80 and 300 μs, corresponding to two decay stages — electron–ion plasma containing negative ions and ion–ion (bielectron) oxygen plasma [3–5, 11]. The $I(t)$ pulse recording has shown that a peak appears in both the electron–ion and the ion–ion plasma, and charac-

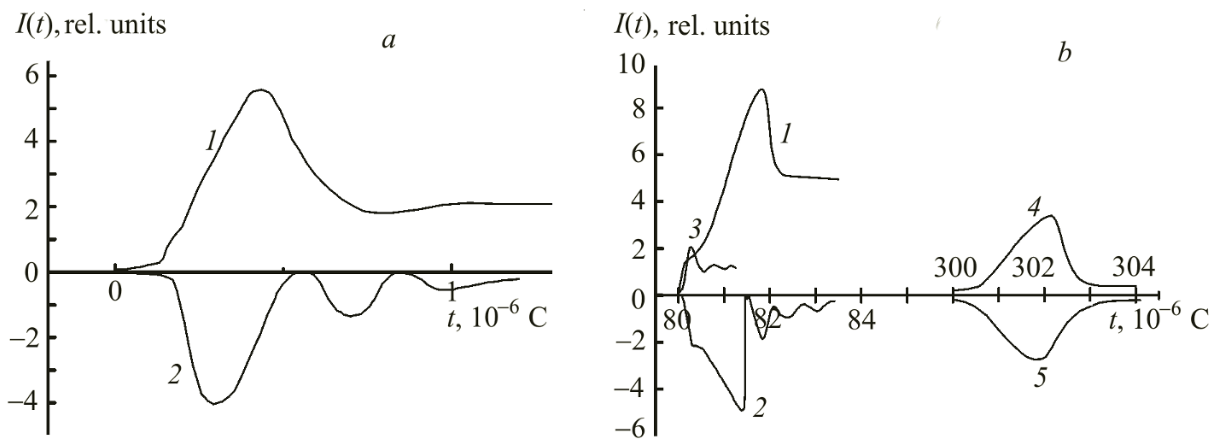


Fig. 2. Displacement current $I(t)$ caused by the charge redistribution in the near-probe layer in the helium plasma (a): 1) electron current of the probe at a potential of –5.5 V; 2) current of positive ions at a potential of 5.5 eV (in this figure the ion current is increased 5 times); and in the decaying oxygen plasma (b): 1, 4) current of negative particles at a potential of 8.3 V; 3) current at a potential of 0.7 V; 2, 5) current of positive ions at a potential of –6.3 V.

teristic $I(t)$ peaks appear at both the leading and the rear edge of the pulse. Figure 2b shows the dependences of displacement current obtained at the 80th and 300th μs of afterglow. Measurements were made for three potentials of the probe: 6, 0.7, and 8.3 V. As is seen from Fig. 2, oscillations are set up only for the layer containing, along with ions, an electronic component. The duration of the first period of oscillations for the negative probe layer is thereby 0.6 μs in helium (Fig. 2a) and 1.3–1.5 μs in oxygen (Fig. 2b), oscillations decay in 1.5 and 4–5 μs, respectively.

Experimental Results and Theoretical Discussion. The time needed for a layer to be formed is usually estimated by (1), and the ion layer thickness is found by the "3/2" law [6]:

$$h_+ \approx \left(M_+/m_e\right)^{1/4} \left(eU/kT_e\right)^{3/4} d \ , \qquad (2)$$

where eU/kT_e is the reduced potential, d is the Debye radius, and the value of the electron layer thickness is usually assumed to be $(M_+/m_e)^{1/4}$ times lower than the ion layer thickness [12]. In the helium plasma $(M_+/m_e)^{1/4} = 9.26$. From the shape of curves 1 and 2 in Fig. 2a it is seen that the peak ratio for helium is $I_-(0.44)/I_+(0.32) = 7.4$, which is very close to the theoretical value of $(M_+/m_e)^{1/4}$. Consequently, this ratio is approximately equal to the value of h_+/h_e. For steady currents with account for the Bohm criterion [1, 12] and the condition $eU/kT >> 10$, $I_e(U)/I_+(U) = (M_+/m_e)^{1/2} \approx 85.7$, but since under the considered conditions $eU/kT_e \sim 9$, the ratio $I_e(t > 1)/I_+(t > 1) = 40$ looks quite reasonable.

Let us consider the oxygen plasma at its late decay stages. As mentioned above, at $t > 230$–250 μs electrons flow onto the tube walls as a result of diffusion and, in the volume ion–ion plasma is formed [3, 4, 11]. The VAC of the steady probe current takes on a symmetric form thereby (curves 1 in Fig. 3): $I_-(t > 303)/I_+(t > 303) \approx 1$. Note the most interesting fact: in the ion–ion oxygen plasma the ratio of peaks also has a practically equal value: $I_-(302)/I_+(301.8) \approx 1$. As we see it, this is due to the comparable masses of oxygen ions (according to the mass-spectroscopic data, the main carrier of positive ions is O_2^+ (86%), and for negative ones it is O^- (90%)) [13]. In this case, for the layer thickness

$$h_+ \approx (M_+/M_-)^{1/4} (eU/kT_-)^{3/4} d \approx (eU/kT_-)^{3/4} d \qquad (3)$$

holds. Since $(M_+/M_-)^{1/14} \to 1$, then, according to (1) and (3), the layer transit times for both positive and negative ions are practically equal, which leads to an equal value and duration of the corresponding current peak.

The most interesting measurements in the oxygen plasma turn out to be those made at early decay stages when the near-probe layer contains electrons and ions of both kinds. At $t = 80$ μs the peak ratio is $I_-(81.7)/I_+(81.3) \approx 2$, and for steady currents at $t > 84$ μs, $I_-(U)/I_+(U) \approx 20$ (curves 1 and 2 in Fig. 2). At this decay stage the main contribution to the current of negative ions is made by the electronic component. The probe VAC has the "usual" form when the current of positive ions is low compared to the current of negative ions (curve 3 in Fig 2). The presence of negative ions leads to a drastic decrease in the thickness of the negative probe layer. In this case, its value is a composite function of the reduced potential eU/kT_e, the relative density a = n_+/n_-, and the temperature ratio $d = T_e/T_-$:

$$\frac{h_+}{d} = \frac{2\sqrt[4]{1+\alpha\delta}(1/\delta + \varepsilon eU/kT_e)^{3/4}}{\sqrt{3}(1+\alpha)^{3/4}},$$

where ε is the screening parameter [3]. The layer thickness at a wide parameter spread is (4–7)d, and $h_+ \approx (1\text{–}3)h_-$ [4]. Thus, under our conditions the ratio between the peak values $I_-(81.7)/I_+(81.3) \approx 2$ points to the ratio of $h_+ \approx 2h_-$.

According to Eq. (2), the layer thickness, all other things being equal, depends on the potential eU/kT applied to the probe: the lower the voltage applied to the probe, the smaller the layer and the faster its formation. From the presented measurements it follows that the minimum delay and amplitude of current are observed at potentials close to the space potential (curve 3 in Fig. 2). Thus, from the presented experimental and theoretical material it follows that $h_+ >> h_- >> h(U_+)$, where $h(U_+)$ is the layer formed when a voltage close to the space potential is applied to the probe. The results of systematic measurements of the oxygen plasma under the given discharge conditions are presented in [4, 11]. The main results of the oxygen plasma diagnostics are presented in Table 1.

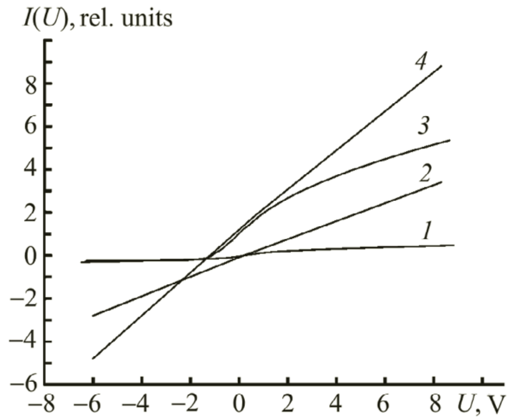
Since in the process of probe diagnostics continuous $I(U, t)$ curves were obtained, we can find, with the use of the given data, the particle density in each decay phase. From Table 1 it follows that the characteristic densities of charged particles in the discharge are ~10^{10} cm^{-3}; T_e decreases from 1.98 to 0.03 eV in 15–20 μs after the discharge pulse ceases. According to the measurements in the ion–ion plasma phase, the temperature of ions, according to the probe theory, is much higher than the T_e value measured in the previous, electron-ion decay phase. This apparent paradox was considered in [3, 4, 11], where it was shown that the high temperature of ions T_i is the instrumental effect of the probe method and is due to the presence of collisions in the space charge layer. In the above works, it was suggested to modify the temperature determination by two methods, 1) by graphical correction of probe curves [2, 5], and 2) by taking into account the layer thickness and the interaction of particles in this layer [3, 4]. The proposed theory has shown that in the ion–ion plasma the layer thickness is practically equal for both negative and positive ions and its value at $t < eV/kT < 5$ can be estimated by formula (2). A further increase in the potential requires taking into account the screening, which was first done in [3]. According to the results of this work, the value of $eU/kT \to \infty$ leads to an ion layer thickness of 5.5 Debye radii. We determine from Table 1 the values of the concentration and temperatures of ions at t = 300 μs: $n = 4.1\cdot10^9$ cm^{-3} and kT/e = 0.03 eV. The Debye radius is 0.0014 cm, and the layer thickness is 0.077 cm. We find the distance that the O_2^+ ion covers with a thermal velocity in the time t = 1.7–2.2 μs corresponding to the $I_-(t)$ current maximum in Fig. 2b from

$$s_+ \approx vt = 0.08\text{–}0.1 \text{ cm},$$

for negative ions $s_- \approx$ 0.11–0.15 cm. In the case of the helium plasma, the layer of the positive probe is measured to be 0.15–0.17 cm, and the distance covered by the positive ion in 0.44 μs is estimated to be 0.23 cm. As is seen, our estimates of the layer thickness and the distance covered by ions in the time of its formation coincide with reasonable accuracy. This points to a close relation between the maximum of the $I(t)$ current spike, the near-probe layer thickness, and the velocity of ions in this layer. Note another important fact: $I_-(t)$ and $I_+(t)$ peaks measured at the 80th μs of decay have practically the same duration as the peaks in the ion–ion plasma, which points to the predominant influence of ions on the near-probe layer formation in the oxygen plasma.

The probe VACs measured at the 80th and 300th μs are given in Fig. 3. As the measurements show, the steady current has an asymptotic dependence $I(U) \sim U^{1/2}$ [3–5, 11]. If we plot the VAC by the displacement current maximum, then as follows from Fig. 3, the characteristic takes on a linear form: $I(U) \sim U$. It was suggested that such a functional dependence is due to the small number of measurements. To refute this judgement, probe measurements in helium were made. The pulse signal was recorded on a Textronix 1012B oscilloscope, and then the VACs of the peaks and steady current were plotted. The measurement data are presented in Fig. 4. From Fig. 4 it follows that for the steady probe current the relation $I(U) \sim U^{1/2}$ also holds, whereas for the displacement current $I(U) \sim U$. Meanwhile, under the described conditions, the linear dependence for the spike can easily be explained with the example of motion of a dielectric plate between the flat capacitor plates. In a closed electric circuit containing an emf source, an electrical resistor, and a capacitor, electric current flows if a dielectric plate is moved at a constant velocity into the capacitor

$$I = \frac{\Delta Q}{\Delta t} = \varepsilon_0\varepsilon\varphi\frac{\Delta C}{\Delta t} = \varepsilon_0\varphi\frac{l}{h}v[1-\varepsilon].$$



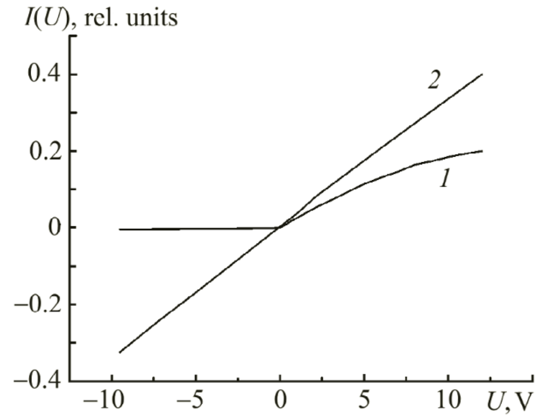


Fig. 3. Volt-ampere characteristic of the probe at the 300th μs of afterglow: 1) of the steady current; 2) of the displacement current; VAC of the probe at the 80th μs of decay: 3) of the steady current; 4) of the displacement current.

Fig. 4. VAC in helium: 1) of the steady current; 2) of the displacement current

TABLE 1. Parameters of the Oxygen Plasma at a Pressure of 0.07 Torrand Discharge Current of 80 mA according to the Data of [4, 11]

t, μs	n_e, cm^{-3}	T_e, eV	n_n, cm^{-3}	T_-, eV	n_p, cm^{-3}	T_+, eV
0	$8.2 \cdot 10^9$	1.98	$6.1 \cdot 10^9$	(0.032)	$1.43 \cdot 10^{10}$	(0.032)
40	$1.86 \cdot 10^9$	0.03	$6.1 \cdot 10^9$	(0.032)	$7.96 \cdot 10^9$	0.032
150	$3.6 \cdot 10^8$	0.029	$5.5 \cdot 10^9$	(0.032)	$6.0 \cdot 10^9$	0.032
230	0	0	$4{,}52 \cdot 10^9$	0.075 (0.032)	$4.53 \cdot 10^9$	0.089 (0.032)
400	0	0	$3.47 \cdot 10^9$	0.075 (0.032)	$3.47 \cdot 10^9$	0.089 (0.032)

Note: t is the moment of measurement of probe curves in decaying plasma (t = 0 is the active discharge phase). Enclosed in brackets are tentative temperature values.

In this case, the displacement current is determined by the voltage U applied to the probe, the formation rate of the near-probe layer v, the probe length l, the layer thickness h, as well as by the difference 1–e(h). The latter expression characterizes the properties of the plasma in the near-probe layer and carries information on the elementary processes proceeding during its formation. Note that the capacity formula for a cylindrical capacitor in which the distance between the plates is small goes over into the formula for a flat capacitor [14].

Conclusions. This paper presents experimental data on probe measurements in oxygen and helium plasma. It has been shown that current oscillations in the positive charge layer are exclusively due to electrons, since in the ion–ion plasma of the negative layer such oscillations are absent. The presence of these oscillations is connected with the layer formation. It is possible that current oscillations are set up as a result of the oscillations of the electronic components in the process of positive ion charge exchange: the motion of electrons is determined by the microfield; the charge exchange changes the direction and velocity modulus of the ion; due to inertia, lighter particles "slip", but the changed microfield forces them to change their trajectory, which causes oscillations. The conclusion that the layer ratio is a function of the ratio of current peaks has been substantiated. This permits determining the presence of negative ions in the near-probe layer. Of no less interest is the development of the concept of dielectric properties of the plasma. The linear dependence of the displacement current on the probe potential permits determining the dielectric constant of the plasma. Thus, the results of experimental investigations of nonstationary currents are presented, and methods for determining the characteristics of near-probe space charge layer in a low-pressure plasma are proposed.

NOTATION

a, probe radius; *C*, capacitor capacity; *d*, Debye radius; *e*, electron charge; *h*, thickness of the space charge layer; *I*, current on the probe; *k*, Boltzmann constant; *l*, probe length; M_+, M_-, and m_e, mass of positive and negative ions and electrons; n_+, n_-, and n_e, concentration of positive and negative ions and electrons; *R*, electrical resistance; *S*, probe area; *s*, motion of ions; T_+, T_-, T_e, temperatures of charged particles; *U*, potential applied to the probe; *v*, thermal velocity of ions; $\alpha = n_-/n_e$, degree of electronegativity of plasma; $\delta = T_e/T_-$, temperature ratio; ε, dielectric constant; φ, emf of the source; $\eta = eU/kT$, reduced potential; τ, characteristic time.

REFERENCES

1. L. Schott, Electric probes, in: W. Lochte-Holtgreven (Ed.), *Plasma Diagnostics* [Russian translation], Mir, Moscow (1971), pp. 499–501.
2. Yu. M. Kagan and V. I. Perel′, Probe methods for plasma studies, *Usp. Fiz. Nauk*, LXXXI, Issue 3, 409–452 (1963).
3. S. A. Gutsev, On the theory of the near-probe layer in ion-ion plasma; deposited at VINITI No. 2956–V97, p. 14.
4. S. A. Gutsev, Investigation of the decaying plasma of electronegative gases, *J. Eng. Phys. Thermophys*., **75**, No. 2, 477–483 (2002).
5. S. A. Gutsev, N. B. Kosykh, and A. A. Kudryavtsev, Account of charged particles collisions, *Vestn. St. Piterburgsk. Univ*., Ser. 4, Issue 4, 153–155 (2013).
6. V. I. Demidov, N. B. Kolokolov, and A. A. Kudryavtsev, *Probe Methods for Investigating Low-Temperature Plasmas* [in Russian], Énergoatomizdat, Moscow (1996).
7. D. Kamkeand H. J. Rose, Die Tragerdichteim Plasma und ihre Bestimmungmit der Impuls-Sonde, *Z. Phys*., **145**, Issue 1, 83–115 (1956).
8. B. T. Barnes and S. Eros, Techniques for measuring the dynamic characteristics of a low charge, *J. Appl. Phys.*, **21**, Issue 12, 1275 (1950).
9. R. Y. Carlson, T. Okuda, and H. J. Oskam, Dynamic Langmuir probe studies, *J. Appl. Phys.*, **33**, Issue 10, 3141–3142 (1962).
10. R. Y. Carlson, T. Okuda, and H. J. Oskam, Studies of the dynamic properties of Langmuir probes l: measuring methods, *Physica*, **30**, 182, 192, 375 (1964).
11. S. A. Gutsev, *Evolution of Unstable Plasma Parameters in Electronegative Gases*, Candidate′s Dissertation (in Physics and Mathematics), St. Petersburg State Univ., St. Petersburg (1997).
12. Yu. P. Raizer, *Gas Discharge Physics* [in Russian], Nauka, Moscow (1992).
13. J. B. Thompson, Electron energy distribution in plasmas. IV. Oxygen and nitrogen, *Proc. Roy. Soc. London*, **A262**, 503–518 (1961).
14. D. V. Sivukhin, *General Course of Physics. Electricity* [in Russian], Nauka, Moscow (1983).